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The Pulsed Linear Induction Motor Concept for High-Speed Trains

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ABSTRACT

The SERAPHIM (SEgmented RAil PHased Induction Motor) concept is a linear induction motor concept which uses rapidly-pulsed magnetic fields and a segmented reaction rail, as opposed to low-frequency fields and continuous reaction rails found in conventional linear induction motors. These improvements give a high-traction, compact, and efficient linear motor that has potential for advanced high speed rail propulsion. In the SERAPHIM concept, coils on the vehicle push against a segmented aluminum rail, which is mounted on the road bed. Current is pulsed as the coils cross an edge of the segmented rail, inducing surface currents which repel the coil. The coils must be pulsed in synchronization with the movement by reaction rail segments. This is provided by a sense-and-fire circuit that controls the pulsing of the power modulators. Experiments were conducted to demonstrate the feasibility of the pulsed induction motor and to collect data that could be used for scaling calculations. A 14.4 kg aluminum plate was accelerated down a 4 m track to speeds of over 15 m/sec (33 mph) with peak thrust up to 18 kN (4040 pounds force) per coilset. For a trainset capable of 200 mph speed, the SERAPHIM concept design is based on coils which are each capable of producing up to 3.5 kN thrust, and 30 coil pairs are mounted on each power car. Two power cars, one at each end of the train, provide 6 MW (8,000 hp) from two gas turbine prime power units. The thrust is about 210,000 N (47,100 pounds force) and is essentially constant up to 200 km/hr (120 mph), since wheel slippage does not limit thrust as with conventional wheeled propulsion. A key component of the SERAPHIM concept is the use of passive wheel-on-rail support for the high speed vehicle. Standard steel wheels are capable of handling over 200 mph. The SERAPHIM cost is comparable to that for steel-wheel high-speed rail, and about 10% to 25% of the projected costs for a comparable Maglev (Magnetically levitated) system. A brief cost and revenue analysis suggests that full cost recovery is possible on intercity routes where the potential ridership is more than 20,000 passengers per mile per year. Such regional routes as the NE Corridor, San Francisco - San Diego, and Los Angeles - Las Vegas appear to be good possibilities.

INTRODUCTION

The application of pulsed, linear induction motor technology for high speed trains is being assessed in a research project at Sandia National Laboratories. This project is called SERAPHIM, for SEgmented RAil PHased Induction Motor. This concept involves the use of rapidly-pulsed magnetic fields and a segmented reaction rail, as opposed to low-frequency fields and continuous reaction rails found in conventional linear induction motors (LIM). These improvements give a high-traction, compact, and efficient linear motor. The pulsed linear induction motor uses technology developed for the Sandia coil gun program for electromagnetic launch. In this program, projectiles have been launched electromagnetically to more than 1 km/s. (Ref. 1)

The SERAPHIM train concept is shown in Figure 1. Electrified coils on the train react against a segmented reaction rail mounted on the roadway. In Figure 1a the reaction rail is composed of reaction plates placed horizontally between the steel rails, while Figure 1b shows a configuration in which the reaction plates are mounted outside the steel rails. The train is supported by steel wheels, either with conventional truck-axle arrangement or independent wheel suspension. The linear induction motor provides motive force by magnetic interaction with the reaction rail. Since wheel-rail friction is not used for traction or braking, wheel and rail wear are greatly reduced. Traction and braking forces are therefore not dependent on adhesion between the wheels and rail, and therefore is not dependent on track environmental conditions or speed. The reaction rail is inexpensive, does not come into mechanical contact with the train, does not experience severe heating or mechanical loads, and thus will not be prone to wear and damage.

Linear induction motors have been used previously in high speed rail tests conducted by the Federal Railroad Administration during the 1970s. Tests at the Transportation Test Center in Pueblo, Colorado, were conducted at speeds over 200 mph with small demonstrator vehicles that used a conventional linear induction motor and passive steel wheels. In a conventional LIM, electrical windings generate a backward moving wave of magnetic flux in a conducting reaction rail, producing a forward force. SERAPHIM operates not by embedding flux in a conductor, but by excluding it. In the double-sided version, pairs of closely spaced coils on the vehicle straddle a segmented aluminum rail, as in Figure 2. The current is pulsed as the coils cross an edge, as shown in Figure 3, remains on until the coil reaches the opposite edge, and remains off as they overtake the next segment. The pulsed magnetic field induces surface currents which repel the coil. In essence, the pulsed coils push off the edges because at the high frequency of operation, the flux has insufficient time to penetrate. Efficient braking is also possible by reversing the phasing of coil pulsing. The full thrust can be applied to brake the train at a maximum deceleration of up to 0.5 m/s^2, or 0.05 g.

Figure 4 shows the schematic of the power distribution, coil sets, and reaction rail. The coils are each capable of producing up to 3.5 kN thrust, and 30 coil pairs are mounted on each power car. Two power cars, one at each end of the train, provide 6 MW (8,000 hp) each. Each power car has two gas turbine prime power units, such as the Turbomeca Eurodyn engine. Power modulators provide the pulsed voltage (4 kV nominal) to the coils; each

modulator powers 6 coil pairs. There are five modulators on each car. The coils must be pulsed in synchronization with the reaction rail segments. This is provided by a sense-and-fire circuit that controls the pulsing of the power modulators. Each power modulator provides about 1.2 MW average power, in pulses of 2 ms half-width, at frequency from 100 - 230 Hz.

The maximum speed is limited primarily by the available power, aerodynamic drag, and grade. For cruise at 200 mph on straight and level track, a power of 6.3 MW (8,500 hp) is required. To meet Federal Railroad Administration specifications for acceleration, however, a maximum power of 12 MW is provided for accelerating from 0 to 350 km/hr (210 mph) in 4 minutes and a distance of 11.7 km (7 miles). With this power capability, the five-car train could climb a 2 % grade at 250 km/hr (150 mph). This power could be delivered by either an on-board or external power source. For a rail line that has the external power capability already in place, such as the North-East Corridor, the use of catenary or third-rail power lines is the obvious choice. However, for rail lines that do not have the external power lines in place, we believe that an on-board power unit is preferred for near-term implementation. Two gas turbine-generator sets on each of two power cars is assumed for our power calculations.

Linear induction motor technology is mature, and has been demonstrated already on a limited basis in high speed rail applications. The performance improvements that can be achieved with pulsed magnets allows the LIM to be modular, compact, and light weight. Introduction of the technology for high speed rail offers the potential for improving the propulsion for high speeds with reduced rail damage. The use of advanced vehicle fabrication techniques and materials could reduce the train weight considerably and reduce the power requirements for high speed acceleration and grade climbing.
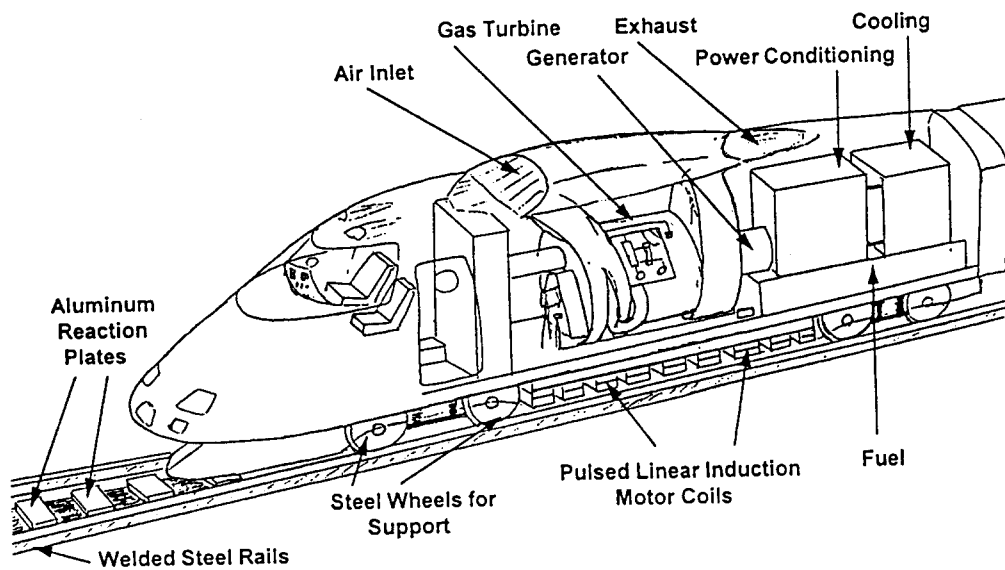
Figure 1a. SERAPHIM train concepts. Horizontal reaction plates located between the steel rails.
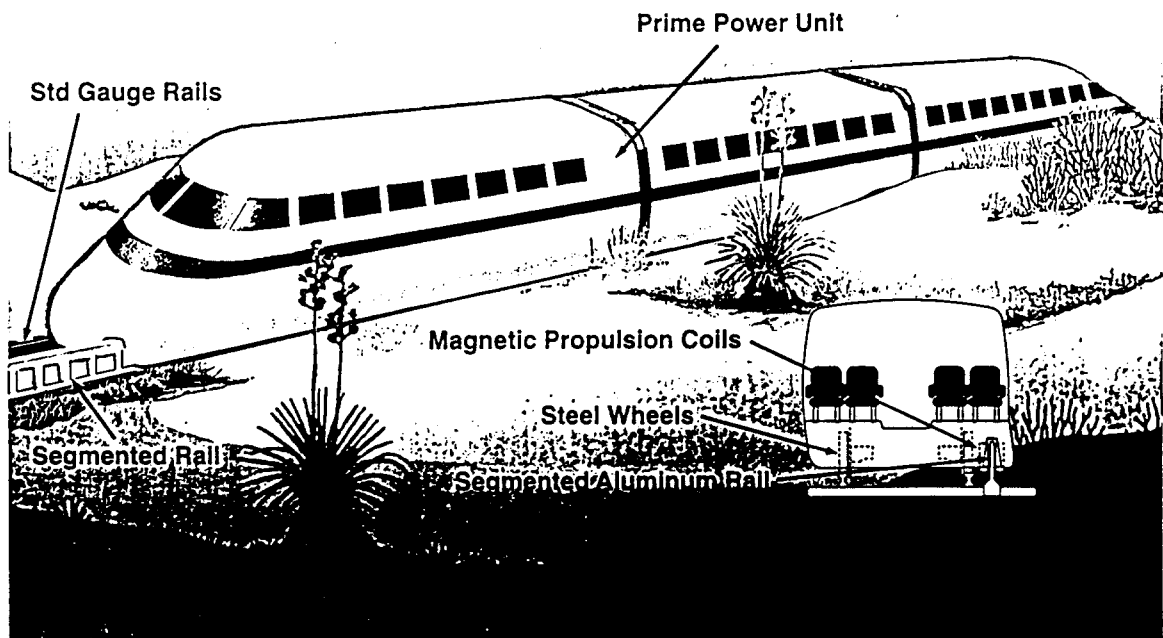
Figure 1b. SERAPHIM train concepts. Vertical reaction plates mounted outside the railway.

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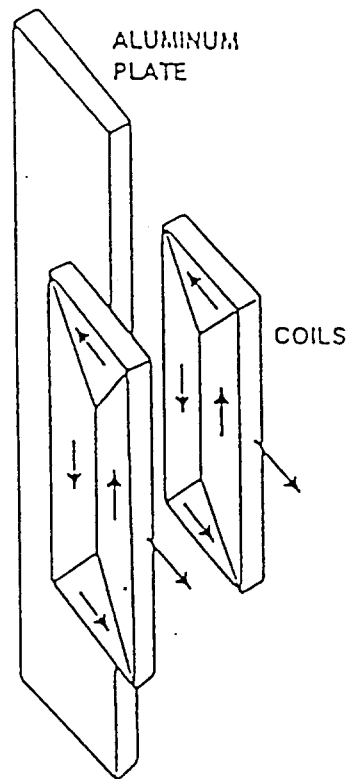
Figure 2. Coil pairs straddle aluminum plate and push of edge.
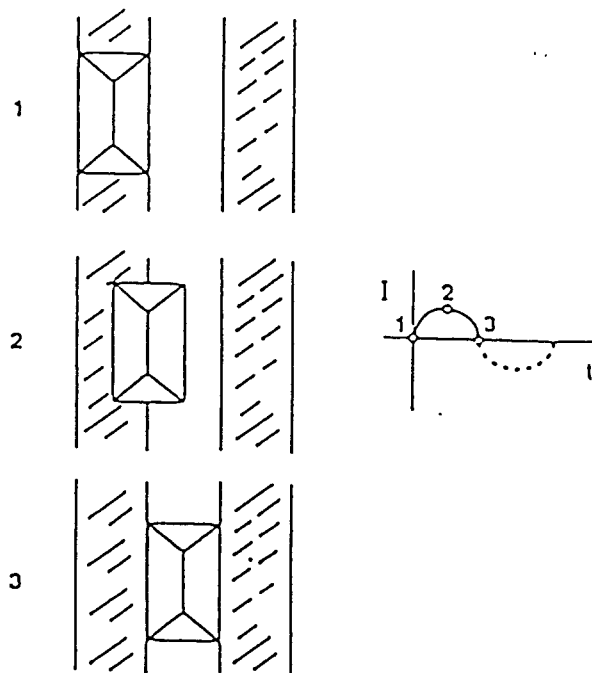
Figure 3. Current is pulsed as coils leave plate and remains off as they move on to the forward edge of the next plate.
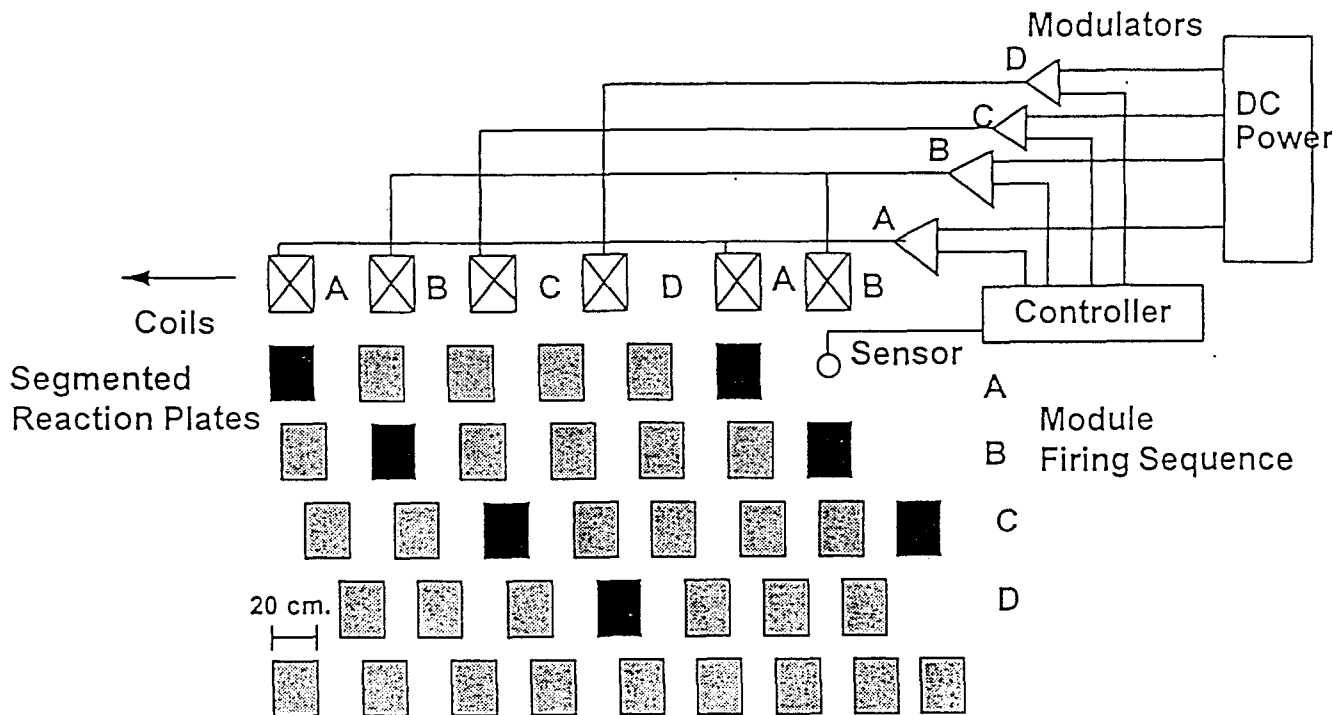
Figure 4. SERAPHIM power circuit. Power modulators produce power pulses to coils when the coils are properly aligned with segmented plates. This schematic shows the firing sequence A, B, C, D as the train moves over the plates. If the individual modules are firing at a frequency f, the effective frequency for the motor is 4f.

THE SERAPHIM DEVELOPMENT PROJECT AT SANDIA

Concept Demonstration Experiments

Sandia National Laboratories has developed the technology of high-power, high thrust electromagnetic launchers for military applications over the past decade. (Ref. 1) This work has been aimed toward electromagnetic guns for Navy fire support and long-range bombardment, and satellite launchers for the Ballistic Missile Defense Organization (BMDO) and the National Aeronautics and Space Administration (NASA). The primary development issues for these concepts were high impulse coils, high peak power switching modules, fire control, simulation, and system analysis. These issues were resolved and demonstrated with a 1 km/second launcher that was tested at Sandia in 1994, supported by BMDO funding. The technical results from this program showed the feasibility of high-thrust launch with electromagnetic coils, and demonstrated techniques for control and power switching.

As a follow-on to development of this technology, Sandia is now testing a lower-power, lower-thrust version of the electromagnetic launcher. This program is aimed at providing a high-thrust magnetic motor for high-speed rail. In this concept, powered coils on the train react with passive conducting plates (called the reaction rails) on the road-bed. In this sense, then, the concept is a linear induction motor, with high-thrust and higher efficiency coming from the use of pulsed-power technology. This program has been funded by the Sandia National Laboratories, through the Laboratory-Directed Research and Development (LDRD) Program.

Experiments were conducted to demonstrate the feasibility of the pulsed induction motor and to collect data that could be used for scaling calculations. We built a three-stage motor demonstration which accelerated a 14.4 kg aluminum rail down a 4 m track to speeds of over 15 m/sec. The experiment configuration is shown in Figure 5. Peak thrust up to 18 kN per coilset was demonstrated. The coils were full scale and operated at much higher field intensity and impulse than required for a passenger train but did not operate repetitively. The energy gain and efficiency were shown to increase with velocity as predicted by the circuit calculations. We varied the driving frequency, vehicle velocity, excitation phase, and energy. The velocity was measured at each stage with fiber optic traps and video framing cameras.

Each coil had two windings of 51 turns of 0.040 x 0.500 inch kapton-dacron insulated copper strap. The coils were all driven with identical damped ringing waveforms triggered with appropriate timing by fiber optic position sensors. Each stage had its own pulse generator, switched by a single ignitron switch computer. Simulations predict an inductance of 3.74 mH for the series connected coils of a stage in free space, and that the presence of the plate can reduce the inductance by almost a factor of two. The total energy per stage was 5 kJ for most of the testing. We used a nominal period of 12 msec.

An aluminum plate of dimensions 20 cm by 40 cm by 2 cm was accelerated electromagnetically as it passed through a pair of pancake coils (see Figure 5). The incident velocity, current, and voltage waveforms were measured. The measured incident velocity

and current were used as input parameters to the numerical simulation of the problem. The electrical and optical diagnostics were augmented by analysis of video recorded television cameras viewing the full acceleration path of the plate. Circuit calculations predicted the resulting exit velocity and this prediction agreed with measurements within 10%. In these low-speed tests the thrust was found to be constant with speed.
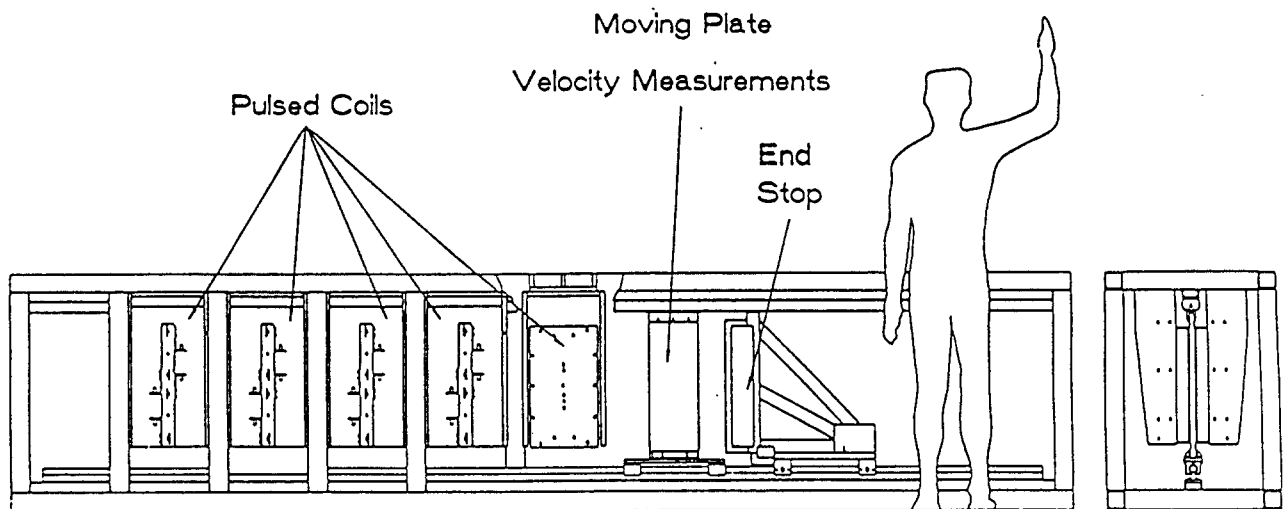
Figure 5. The SERAPHIM Propulsion Demonstration accelerated an aluminum plate by pulsing stationary coils.

In summary, the prototype experiment delivered:

Peak Thrust: T_p = 18 kN;
Average Thrust (50% duty Cycle): T_{ave} = 9 kN
Average acceleration a= 56 m/s^2;
V_o = 3 kV, I_p = 1.3 kA; E_o = 5 kJ/stage.
T_{ave}/E_o = 1.8 kN/kJ

Further tests were conducted with a smaller capacitor, solid state switching, and energy recovery circuit as would be used in the SERAPHIM power modulator circuit discussed in the next section. This circuit used a 263 μfd capacitor charged to 4 kV, with energy of up to 2.1 kJ. The thrust provided by this capacitor discharging into the coil-set was measured from a static start. The average thrust, over one complete discharge cycle, for 2 kJ initial energy, was 6.5 kN, or 3 kN/kJ. The scaling of thrust with initial energy is used in the next section to calculate train motor parameters from the requirements for thrust and number of coils.

SERAPHIM Motor Drive

The drive circuit that appears best suited to the SERAPHIM motor is illustrated
schematically in Figure 6. This drive circuit is basically a pulse modulator which generates a
high current pulse train required to energize the drive coils and can be operated at a
continuously variable pulse repetition rate from single pulse to approximately 500 Hz. Prime
power is supplied by a DC generator or an AC alternator/rectifier.

An important feature of the modulator is that it provides energy recovery following each
pulse. With the circuit configured as shown in Figure 6, a full sinusoidal current cycle is
delivered to the coils, as shown in Figure 7a. Energy not lost to heat or converted to motion
by the coil and reaction plate is returned to the storage capacitor C_{sn} during the second half-
cycle and is trapped by the anti-parallel diode D_{sn} at the original polarity of C_{sn} when the
current goes to zero (Figure 7b). Preliminary measurements of the energy recovery efficiency
of this circuit indicates over 80% recovery of the energy that was originally in C_s.
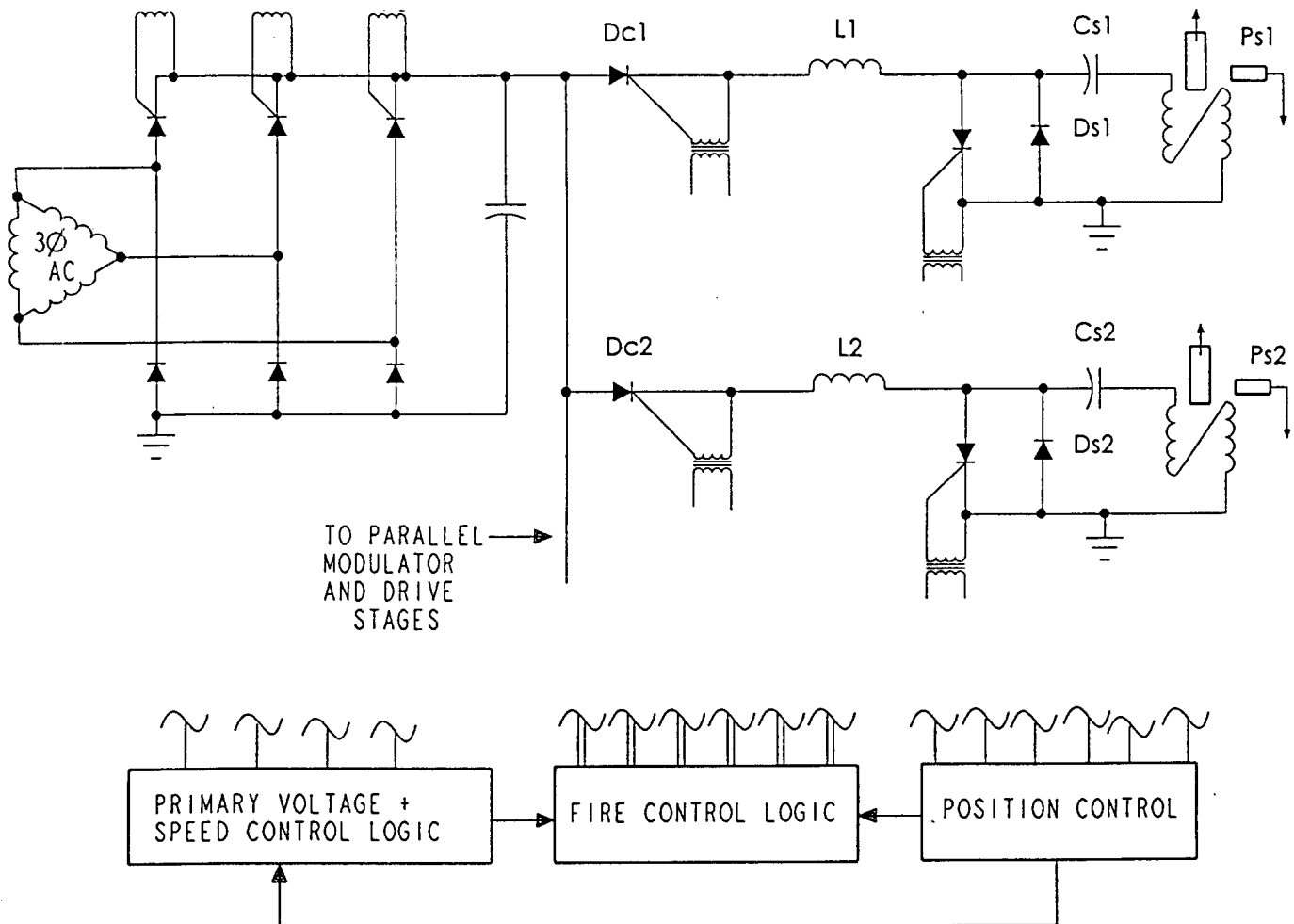
Figure 6. SERAPHIM Drive Circuit

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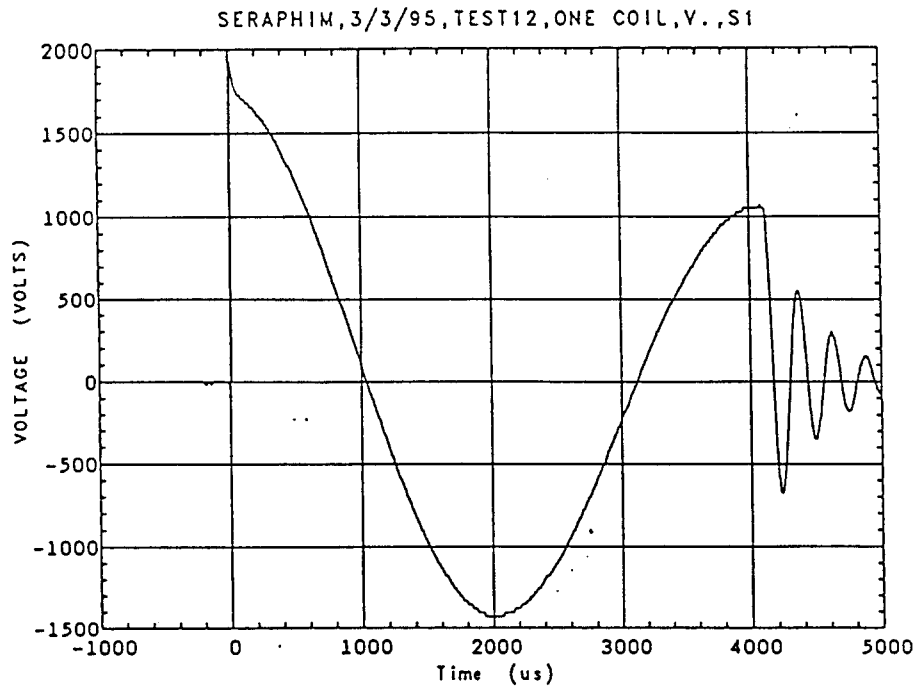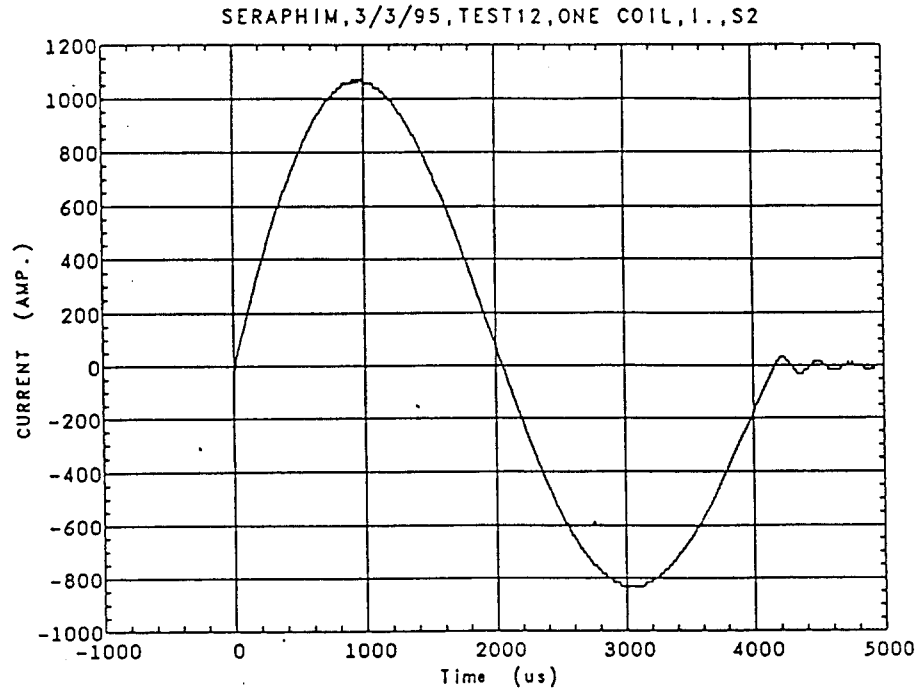
Figure 7. Voltage and current waveforms from the modulator circuit in Figure 6; a) current, and b) voltage, showing the recharging of the capacitor and recovery of energy remaining in the circuit. In this case, 47% of the original energy has been recovered.

Table 1 gives a summary of the weight and volume estimates for the power switching electronics for a power modulator sized for a single coil set (125 kW). This modulator could be mounted at the location of the coil-set, or more likely housed within the power car or locomotive body and connected to the coils by high voltage cables. Some volume reduction can be gained by combining these modules into power packs that drive multiple coil-sets, for example 6 coil-sets driven by each modulator power pack. The optimum design of the power modulator system will be controlled by convenience of location, accessibility, cable connections, and cooling requirements.

Table 1

125 kW Power Modulator Weight and Volume Estimates

	Weight/lb.	Volume/ft.^{3}
Charging Thyristors, Tcn	1.0	.1
Charging Inductors, La	10	.5
Charging Diodes, Dcn	1	.05
Pulse Drive Thyristors, Tsn	10	.5
Charge Recovery Inductor/Diode, L_m & D_m	5	.2
Driver Capacitor, C_{sn} (With Cooling)	50	.7
Misc. (Brackets, Containers, Fans, etc.)	15	2.0
Totals	**86**	**4.05**

A demonstration model for this modulator circuit has been fabricated and tested. The modulator is shown in Figure 8. This circuit has been used in pulsing a coil-set and measuring thrust, as discussed in the previous section. The energy recovery efficiency has also been measured, exceeding 80%. The modulator was made from off-the-shelf capacitors and solid-state thyristor switches.
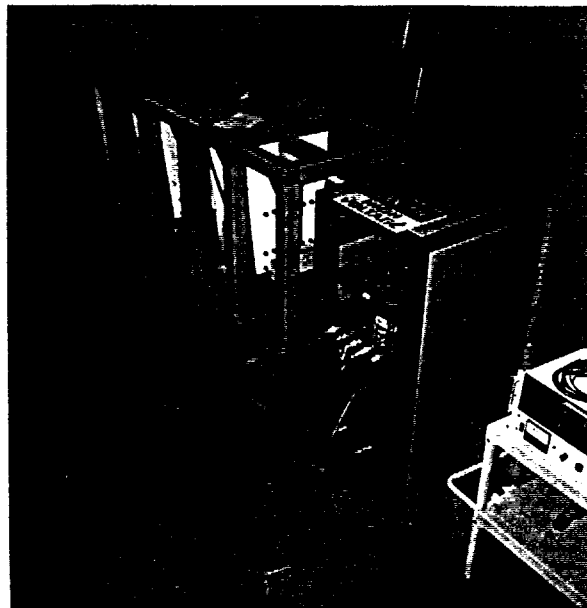
Figure 8. Experimental set-up for the demonstration coils and power modulator.

SERAPHIM can be configured either with double-sided coils, as shown in Figure 2 and tested in the feasibility tests, or single-sided, as shown in Figure 1a and b. In the single-sided case (Figure 1a), the reaction rail lies flat on the ground between the steel support rails. The disadvantage is that, for a given amount of input energy, a smaller force is exerted. Since the force is the change in energy divided by the relative distance traveled by the plate, the configuration which produces the most energy difference is the more effective. The two-sided geometry (Figure 1b) is the more efficient in converting to mechanical force. This does not mean, however, that the single-sided configuration is unacceptable. With energy recovery in the power circuit, we can still maintain good overall efficiency for the single-sided configuration. The price paid is in increased circulating power for the single-sided configuration.

Reaction Rail Design Concepts

The reaction rail is composed of aluminum plates (50 x 20 x 2 cm) that are attached to either a rail for a double-sided configuration or a structure located on the ties between the tracks as illustrated in Figure 1a and b. The reaction plates are subjected to forces that have parallel, defined as thrust, and normal components. The pulsed forces are related to the positions of the coils relative to the plates as shown in Figures 2 and 3. From a design standpoint, maximum thrust forces of 3.5 kN per plate occur at the coil pulsing frequency. The power loss in eddy current is about 30 kW (15% of the electrical power into the coils) for about 1 second duration during the passage of the train. Thus the aluminum plate absorbs about 30 kJ of energy, and the plate temperature increases by less than 10° C. Maximum normal magnetic pressures are obtained from the coil field interaction with the reaction plate, using the design gap of 1 cm. Using a field of 2 T, it is estimated that the maximum normal magnetic pressure for a coil on a plate is approximately 414 kPa (60 psi).

The supporting structure for the reaction plates could have one of four basic design configurations:

1. In the first, horizontal plates can be attached directly to the cross ties and each plate acts as an independent unit. The advantage is that plates and underlying ties can be easily replaced and this is the cheapest rail. We estimate that the cost to install the plates on the railway ties is $240k/mile. One disadvantage is the difficulty in anchoring plates to somewhat non-uniform ties. The locomotive or power car would require an undercarriage mounting structure for the coils, with about 1 cm clearance to the reaction rails. This will require close tolerance in mounting the reaction rail and undercarriage structures, and a means of sweeping debris from the reaction rail.

2. The second configuration is to firmly attach the horizontal plates to a long rail-type structure that rests on the ties. The plates can be attached to light gauge aluminum or steel hat-shaped sections that can be attached to the cross ties. It is assumed that two parallel sections, each approximately 9 cm wide and 2 cm thick, could support the plates and maintain proper alignment. These supporting sections would distribute the thrust and normal forces to the cross ties over a relatively long distance. The

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supporting rail would have to be designed to prevent dynamic buckling mechanisms due to traveling compression waves generated by the moving train. The cost for this option is estimated to be $280k/mile.

3. The third configuration is to locate a rail structure between the ties and use reaction plates that are oriented vertically. This has the operational advantage that the thrust is centered and coils can be mounted compactly on the power car. Disadvantages are that a more substantial reaction rail system must be installed and also that the locomotive/ power car must be designed to straddle the rail with the coils. This configuration will not be compatible with conventional trains, and will necessitate dedicated railways. Using a similar construction technique to Case 2, but mounted vertically, the cost estimate is $350k/mile for reaction rail fabrication, installation, and track modification.

4. A fourth configuration is to locate the reaction rail structures parallel to and outside the main tracks, as shown in Figure 9. The reaction plates could be attached to lightweight support sections as discussed in Case 3, with the sections placed on tie segments outside the tracks at the ends of the crossties. The coils are mounted externally to the power car in possibly a more complex structure than the other cases. Since there is considerable overhang of the power car beyond the width of the rails, there is adequate space to mount this coil structure within the existing width of the power car. There will be adequate clearance between passing trains, and adequate space on the roadbed for mounting the reaction rails. The cost for a single reaction rail is estimated to be $350k/mile. This single-sided configuration produces thrust from only one side of the train, and this asymmetric thrust must be compensated. If rails are mounted on both sides of the track, then thrust symmetry is restored, but the rail cost may be doubled.

While we are continuing to evaluate the advantages and disadvantages of all these options, we assume for the remainder of this study that Option 4, with single reaction rail at a cost of $350k/mile, will be used for costing purposes.

An important factor to consider in applying any of the reaction rail configurations is that of clearance between the static and moving parts. The Linear Induction Motor Research Vehicle (LIMRV) test results (Ref. 7) showed a 3σ gap variation of 0.2 inches (0.50 cm) at speeds up to 190 mph (316 km/hr). The 3σ off-set data for the LIM gap on the LIMRV is shown in Figure 10. Therefore, the gap spacing for SERAPHIM is taken at 1.0 cm, to allow a factor of two safety margin from the LIMRV data. For current trains, the Federal Railroad Administration requires a minimum clearance of 6.3 cm (2.5 in) above the top of the tracks for cars and locomotives. For any of the four configurations presented, special provisions would have to be legislated for operation of SERAPHIM, as the gap would be approximately 1 cm (0.4 in).

Obviously, designs involving horizontal plates would have to include effects of removing undesirable objects resting on the reaction plates and such conditions as wind-blown sand

being deposited on and between the plates. Designs involving vertical plates on rail structures would have to account for objects inadvertently being placed on the rails.
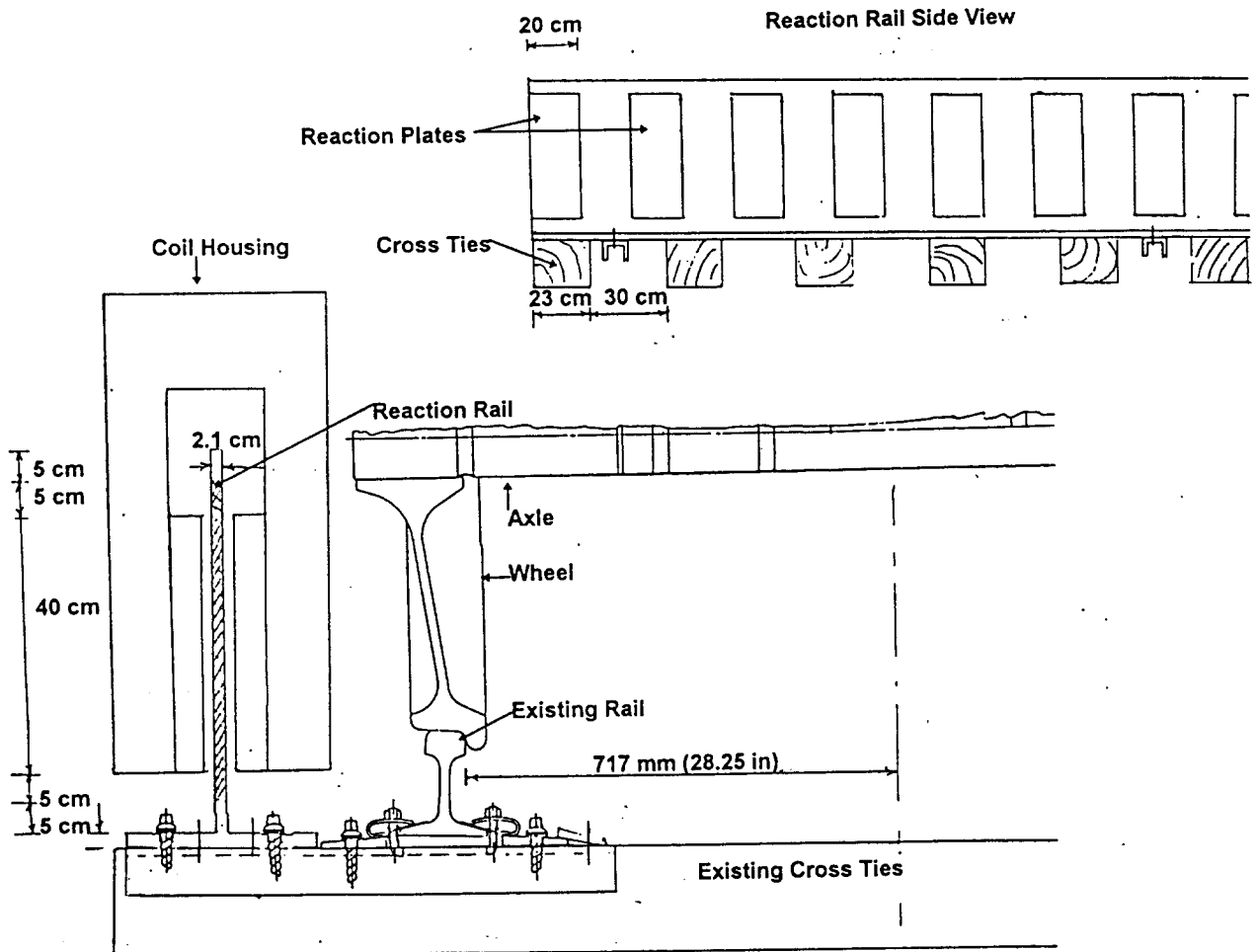
Figure 9. Layout of the reaction rail mounted outside of the track.
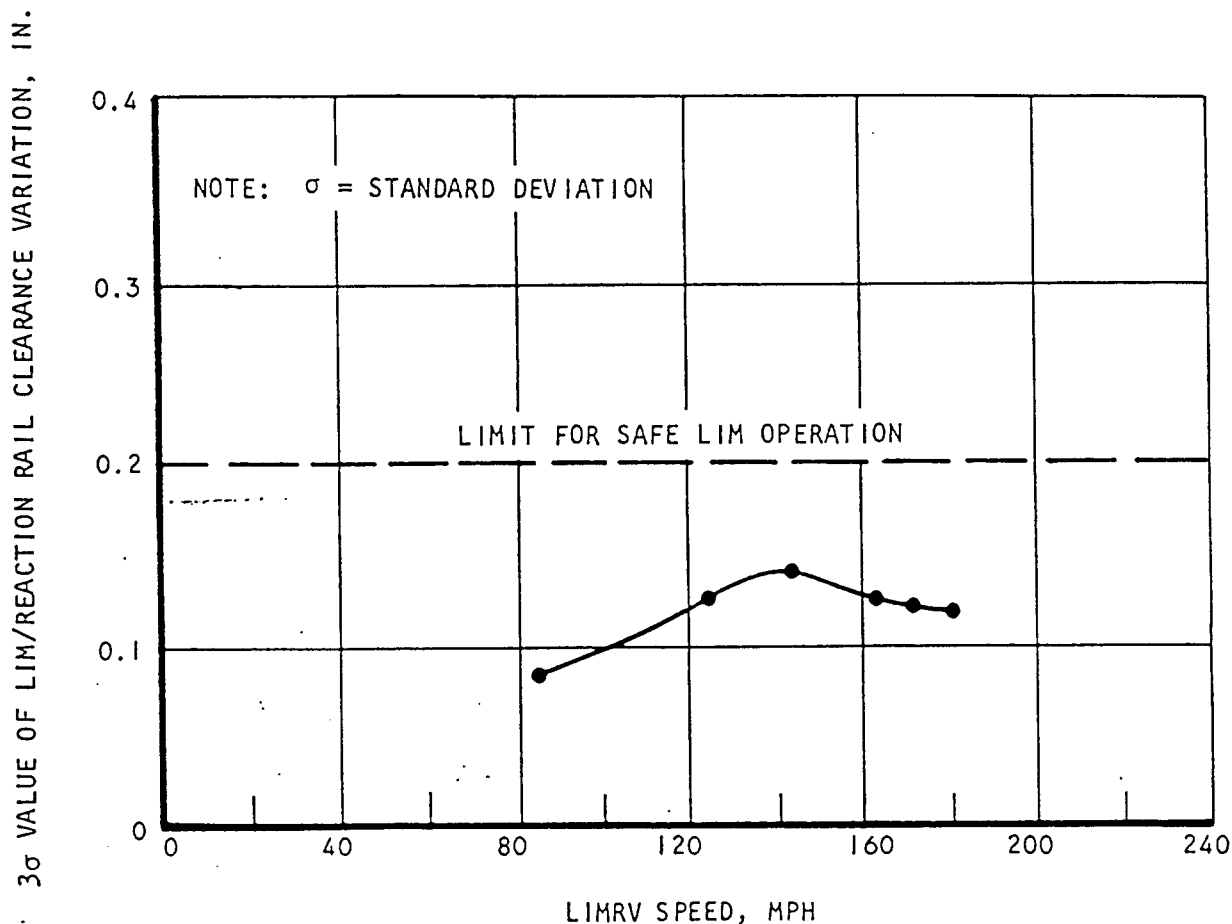
Figure 10. Three-sigma value of LIM/reaction rail clearance variation vs. vehicle speed. (Ref. 7)

Wheel and Suspension Study

A key component of the SERAPHIM concept is the use of wheel-on-rail support for the high speed vehicle. Standard forged steel wheels of good quality are capable of handling speeds over 200 mph as long as there is no tread braking. The French TGV demonstrated 515.3 km/hr (~ 309 mph) on a straight track as part of demonstration tests. TGV wheels have a diameter of approximately 1 meter and are made from UICR7, a heat treated 0.6% carbon steel. (Ref. 2) This wheel composition overlaps American Association of Railroads (AAR) Specification M-107-83, Classes A and B. A preliminary material specification similar to the TGV wheels would include specific melting and material cleanliness standards, a nominal carbon content of 0.55 - 0.65% carbon, and rim heat treatment to a Brinell hardness of about 300 BHN.

Wheel dimensional and dynamic balance characteristics are also critical to the successful use of wheel-on-rail support at high speeds. The TGV wheel specifications limit the out of round condition to 0.1 mm maximum per wheel. Additionally, wheels mounted on the same axle are specified to have less than 0.1 mm difference in size, and wheels mounted in the

same bogie are required to have less than 20 mm difference in size. (Ref 2) All wheels are dynamically balanced. Similar requirements would be necessary for a SERAPHIM vehicle.

Long-term operation at speeds over 200 mph has not been evaluated, and could be an important issue for the full-speed SERAPHIM concept. However, this issue should be addressed during a detail design phase if the concept is pursued. The primary wheel loads of the fastest conventional trains in the US, up to 150 MPH, result from the thermal and mechanical loads of tread braking. The SERAPHIM concept would not utilize tread brakes, but would utilize a combination of electromagnetic braking at high speeds and disk brakes at lower speeds. Adequate inspection methods and frequencies will be specified to ensure that wheel integrity is maintained over the wheel design life.

Lightweight wheel design concepts could be pursued if deemed worthwhile during advanced design. Bimetallic wheels consisting of aluminum hubs with shrink-fit steel tires are already used in some light rail systems. These wheels are 35-40% lighter than an all-steel wheel having the same shape. Bimetallic wheels should be capable of operation up to speeds of 200 MPH although they have not been analyzed for operation in the high speed range. Advanced aerospace materials could be applied to produce lighter wheel hubs with appropriate stiffness characteristics. Detailed cost-benefit studies would be required to determine if using titanium alloys, high strength maraging steels, or composite materials would make sense for wheel applications in light of the operational and maintenance requirements.

The simplest means of attaching the wheels to the carbody structure is to use a conventional rail truck arrangement with solid axles and rigid side bolsters. A common arrangement has disk brakes mounted on the axles. Conventional trucks have been designed and tested for continuous service up to 200 mph. (Ref 3) TGV trucks and suspension components were tested to 309 mph as mentioned above.

Conventional trucks allow tuning of the ride characteristics through primary and secondary suspensions, and allow car tilting mechanisms to be incorporated. However, they tend to be massive and heavy. Advanced trucks have been designed and tested with independent wheels, i.e. each wheel mounted on a short, independent axle shaft, and have been found to be feasible. Designs of truck frame structures and axles using carbon fiber composites are being evaluated. An ultra-light truck assembly could be designed using carbon fiber composite frames and bolsters, with independent wheels or carbon fiber composite axles, and lightweight bimetallic wheels. This may be the most practical suspension design for an operational SERAPHIM vehicle because such a design would remove well over half the weight from a conventional wheel and truck assembly.

Alternative suspension concepts have also been envisioned. Since the fuselage of a high speed train vehicle will have structural characteristics similar to an aircraft fuselage, trucks could be incorporated into the frame of the carbody instead of being a separate unit. This could be done with or without axles connecting wheels. The weight of the suspension assembly could be significantly reduced by eliminating the trucks, and directly attaching the wheels to the car with a McPherson Strut type of assembly or trailing link/torsion bar type of

assembly. Independent wheels/suspension system requires that alignment be adjustable like a sports car, setting toe-in, caster, camber. This can be used to advantage by setting wheels to track straight without the "hunting" (side to side dynamic instabilities) which can occur with conventional truck assemblies at specific speeds due to fixed geometry of wheels tied to a solid axle. An advanced design could allow wheels to tilt into curves slightly to minimize curve forces. If the suspension is mostly enclosed in the car body with only some portion of the wheels sticking out of slots in the fuselage, this could improve the noise level and possibly the aerodynamics of the vehicle. All of these concepts would require significant design effort to assess feasibility and evaluate the effect on total vehicle cost and performance.

Aerodynamic Analysis

Because of the high speed projected for the SERAPHIM train, aerodynamic drag will be the primary factor determining power requirements at near maximum train speeds. The aerodynamic drag, D_a is given by $D_a = (1/2\rho V^2)C_d A_s$, where ρ is the air density, V is the air speed, C_d is the drag coefficient, and A_s is a reference area, typically taken as the frontal cross-sectional area. Airload power, P_a, is simply force moving through a distance per unit time, and is therefore $P_a = VD_a$.

Drag force derives from two basic mechanisms, pressure drag and turbulent skin friction drag. The pressure drag on the train aeroshell is largely a function of the shape of the nose and tail ends of the train, and is usually only weakly dependent on length. Pressure drag due to distributed components, such as suspension trucks, is proportional to train length. Likewise, skin friction drag is directly proportional to train length.

Skojvist (Ref. 4) presents an evaluation of train drag for a variety of train types, including the highest-speed passenger trains in commercial operation, the French TGV, British HST, and Japanese Shinkansen trains. From published data of motive power versus velocity (assuming still air and no grade), Skojvist has generated quadratic fits for the total drag of the form $D=a +bV + cV^2$. The 'a' coefficient term represents static drag, the 'b'-coefficient term represents an effective rolling resistance proportional to velocity, and the quadratic term ('c'-coefficient term) is the aerodynamic drag, D_a. The aerodynamic drag is due to the pressure drag from all sources, and to turbulent skin friction drag, as noted above. Skojvist gives one example, the TGV Sud-Est train (2 power cars and 8 passenger cars), for which the total aerodynamic drag coefficient from all sources is approximately 1.5. For the TGV Sud-Est, Skojvist identifies the various individual contributions to aerodynamic drag. Forty percent of the aerodynamic drag is due to the pressure and skin friction drag on the power cars and passenger coaches (aeroshell, inter-car gaps). An additional 40% is due to the aerodynamic drag on the trucks and undercarriage. The remaining 20% is due to the pantographs (overhead electric power), other roof-mounted equipment, and the disc brakes. The contribution to the total C_d due to the engines and passenger cars alone (without trucks) is therefore 0.6, in excellent agreement with data, after adjustment for train length, given by Hoerner (Ref. 5) for an aerodynamically "ideal" train. The integrated contribution of the trucks, 0.6, is quite large. It is assumed that the use of independent wheel suspensions and fairings would reduce the aerodynamic drag of the wheels and undercarriage, perhaps by as

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much as a factor of two, to a value of approximately 0.3. Conversely, we assume that the drag of roof-mounted equipment for an overhead-line (catenary) powered train cannot be reduced significantly; hence, the contribution to C_d is taken to be 0.3 (for on-board power, this contribution will be zero). Therefore, for a self-powered train otherwise identical to the TGV Sud-Est, $C_d = 1.2$. If, as noted above, the aerodynamics for the wheels, suspension, and undercarriage could be improved by a factor of two, C_d would decrease to 0.9. A reasonable expectation is that the total drag coefficient can be reduced to 1.0 for a self-powered, wheel- or monorail-suspension train consisting of two power cars and eight passenger coaches of optimized aerodynamic design. It is not known whether significant improvement beyond that will be possible, however. For a catenary-powered train of improved aerodynamic design, the minimum probable C_d will be about 1.2.

Train drag coefficient for different train lengths can be expected to vary approximately in direct proportion to length, with a minimum C_d of about 0.3 for a train consisting of a single power car of optimum aerodynamic design. For such an optimized design, each additional car will increase C_d by about 0.075. For current high-speed train designs, typified by the TGV, each car will increase C_d by about 0.10.

It is noted that there appear to be very large variations in the curve fit-derived a, b, and c coefficients presented in Ref. 4. The source of these variations is not fully understood, but is due, in part, to inaccuracies in the power data as a function of velocity, variations in drag area A_s and train weight, and variations in train aeroshell and suspension design. The large variations may also reflect statistical fluctuations due to inadequate quantities of data. Each coefficient is approximately proportional to train length, with large statistical uncertainty. No indication of the uncertainties is given for the individual coefficients, however. Of the coefficient sets presented in Ref. 4, the values for the TGV are judged to be the most reliable since they are derived from several independent sources, and appear to be generally consistent.

Based on the data given by Skojvist, a, b, and c are each approximately proportional to train length for high-speed trains, as noted above. It is reasonable to assume that for a given train length, the 'a' and 'b' coefficients will not be subject to significant improvement, and thus will vary little with future train design. The improved value of 'c' corresponding to $C_d = 1.0$ (as suggested above for a self-powered train of optimum aerodynamic efficiency) is c =0.00042. Again using the TGV Sud-Est train as a representative example, a = 3.82 and b = 0.0390. Following Ref. 4, a, b, and c are scaled such that the drag is in kiloNewtons for velocity in km/hr. Therefore, $D = 3.82 + 0.0390V + 0.00042V^2$ kN for a train consisting of two power cars and eight coaches. At 320 km/hr (200 mph), D = 57 kN (12,800 lb$_f$) and P = 5.1 MW (6,560 bhp). Total drag and power for a five-car set [two power cars and three coaches of 88 meter (290 ft) length and weighing 390,000 kg] would be reduced to approximately 63% of the above values, i.e., 36 kN (8,060 lb$_f$) and 3.2 MW (3,110 bhp), respectively. These values are well below the FRA requirements for thrust (180 kN, 40,400 lb$_f$) and power (12 MW, 15,400 bhp) for acceleration and grade-climbing for a (five-car) train of 390,000 kg gross weight. Hence, aerodynamic drag will affect energy efficiency for high-speed cruise, but does not dictate the maximum thrust capability or the amount of installed power.

In summary, we suggest $C_d = 0.65$ for initial predictions of airload power requirements for a wheeled, 88-meter long, 390,000 kg SERAPHIM train consisting of five cars and running on tracks or suspended in a monorail configuration. Although this is a somewhat optimistic choice in that it assumes that a substantial reduction ($\approx 50\%$) in wheel set and undercarriage drag can be achieved through careful design, we believe it is not unrealistic. C_d for other train lengths can be estimated as indicated above.

SERAPHIM HIGH SPEED TRAIN REQUIREMENTS

Train Set Assumptions and Scoping Parameters

Table 2 is a summary of the important parameters for a conceptual vehicle design based on SERAPHIM propulsion. In the SERAPHIM train concept, the individual cars carry 72 passengers each, and multiple cars are connected together for a train "consist." The train set may be powered either from a locomotive or from an electrified line. The SERAPHIM motor is inherently a distributed motor, with each power car having a linear motor consisting of 30 coils. In principal, each passenger car could be equipped with a linear motor, but the added complexity for powered passenger cars is not required for the traction force and power requirements at 200 mph.

Power requirements are estimated from friction loss and aerodynamic drag, as discussed in a previous section. At 200 mph, the cruise power requirement is about 6.3 MW for a 5-car train set, as shown in Figure 11. Acceleration requirements are taken from the Federal Railroad Administration goals for the Next-Generation High Speed Rail Program (Ref. 6). The acceleration requirement from FRA is to travel a distance of 5.8 km (3.5 miles) in 2.5 minutes, and 11.7 km (7 miles) in 4 minutes. This requires an acceleration of 0.5 m/s^2 for the first segment and an acceleration of 0.4 m/s^2 for the second. For a train weight of 390,000 kg, the thrust must be 210 kN. The maximum power requirement is 12 MW. With this thrust, the train can climb a 2% grade at 170 mph.

Table 2
SERAPHIM-200 Scoping Parameters

Vehicles

Passenger Vehicle Width	3.5 m
Height	3 m
Length	18 m
Cross-Section	10 m^2
Number of Passengers	72
Weight	66,000 kg
Locomotive Vehicle Weight	95,000 kg
Number of Vehicles in Train	5
Number of Wheels per Vehicle	8
Size of Wheels	36 inch diameter
Number of Vehicles in Trainset	2 Power Cars
	3 Passenger Cars
	216 passengers
Total Weight of Trainset	390,000 kg

Power Requirements:	12 MW (9000 hp)
Maximum Acceleration	0.5 m/s^2
Maximum Thrust	210 kN
Maximum Speed	200 mph
Drag Coefficient	0.35
Total Drag	36 kN @ 200 mph
Maximum Grade	2.0% @ 170 mph

Coils:	
Power per Coil	200 kW
Coil Dimensions (L x W x H)	40 x 20 x 10 cm
Field	2 T
Frequency	100 -230 Hz
Thrust/Coilset	3.5 kN
Number of Coilsets	30/power car x 2 power cars
Coil cost	$1k per coil

Reaction Plate Dimensions:	50 x 20 x 2 cm
Separation Gap	1 cm
Reaction Force on Plates	5 kN
Cost	$350,000/mile
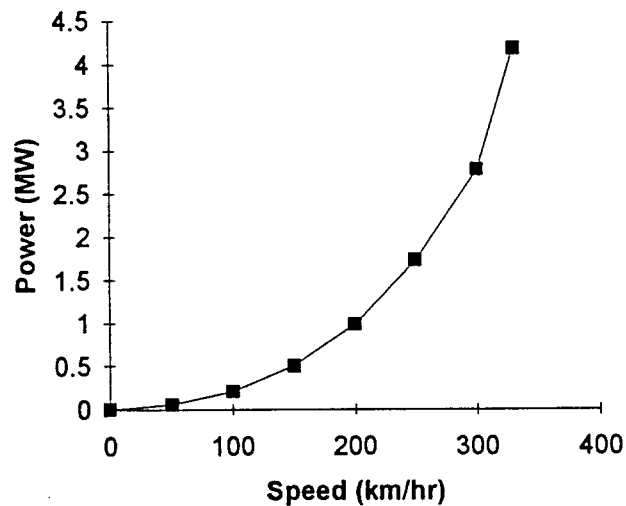
Figure 11. Drag power requirement versus speed

If we assume an average thrust of 3.5 kN per coil, then each power car will need 30 coils to produce the required thrust with two power cars. Using the measured conversion factor of 3 kN/kJ, then each coil-set must be energized with 1 kJ per pulse. The maximum power from each coil set at peak frequency is 200 kW. The power dissipation from these coils will be similar to that experienced with the Linear Induction Motor Research Vehicle. (Ref. 7) That test vehicle used forced air cooling for the propulsion coils.

The thrust profile for the SERAPHIM motor is shown in Figure 12. The thrust is constant with speed (at peak pulse frequency), until the thrust becomes power-limited. Beyond this speed, thrust is inversely proportional to speed, since thrust multiplied by velocity is equal to power.

Figure 12 compares the expected thrust for the SERAPHIM motor with that which can be obtained with multiple modules of a conventional linear induction motor, represented by the LIMRV motor data. (Ref. 7) For a given power level of 12 MW, about 50% more thrust is expected to be provided by the pulsed SERAPHIM LIM.

Wheel slip is the principal limit for traction power and braking for conventional locomotives The "adhesion limit" is an empirical relation between the wheel-rail adhesion factor and the speed of the locomotive. Figure 13 compares the expected thrust profile for SERAPHIM with the adhesion limit for conventional steel on rail propulsion. The adhseion limit is calculated from the Japanese National Railways Shinkansen Network Design Rules (Ref. 4), using two power cars weighing 95,000 kg each. As can be seen from Figure 13, the adhesion limit drops quickly with speed. The magnetic propulsion from SERAPHIM is not adhesion limited, and can maintain high thrust at high speeds, limited only by the available power. This additional thrust is important in providing acceleration and grade-climbing capability. The

Federal Railroad Administration (FRA) acceleration goals (Ref. 6) are shown in Figure 14, showing the calculated distance and speed vs. time for the SERAPHIM-powered and conventional wheel and rail options. Note that SERAPHIM exceeds the FRA distance goals, and achieves a top speed of 340 km/hr (200 mph). The steel wheel on rail propulsion is limited by adhesion, does not meet the FRA goal for distance, and has a top speed of 230 km/hr (140 mph).
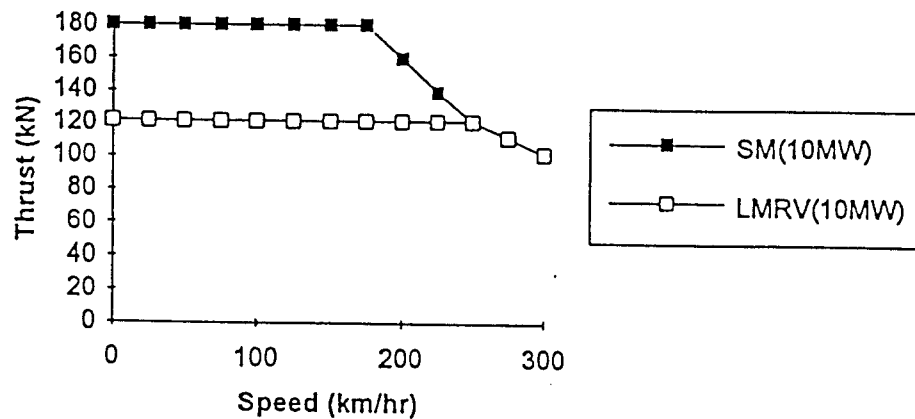
Figure 12. Comparison of thrust for SERAPHIM (SM) and conventiona LIM (LMRV), for 10 MW power.
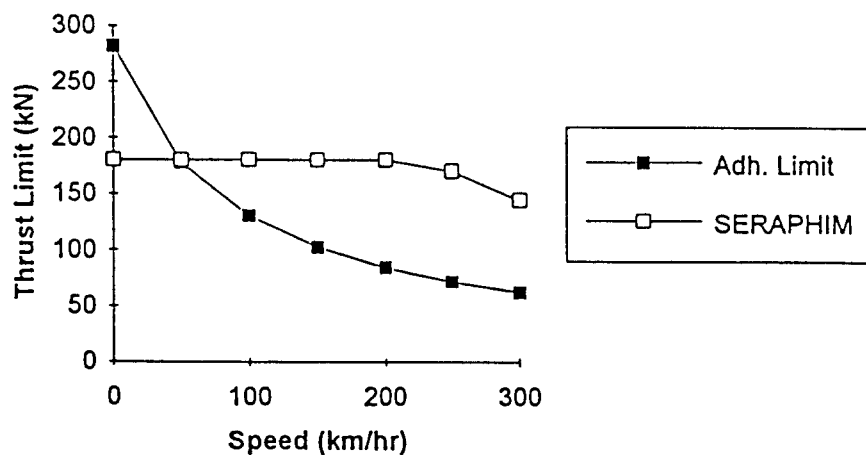
Figure 13. Comparison of thrust for SERAPHIM and adhesion limit for conventional steel wheel and rail propulsion.

Adhesion-Limited RTL-II (5 MW)	SERAPHIM Magnetic Propulsion (10 MW)
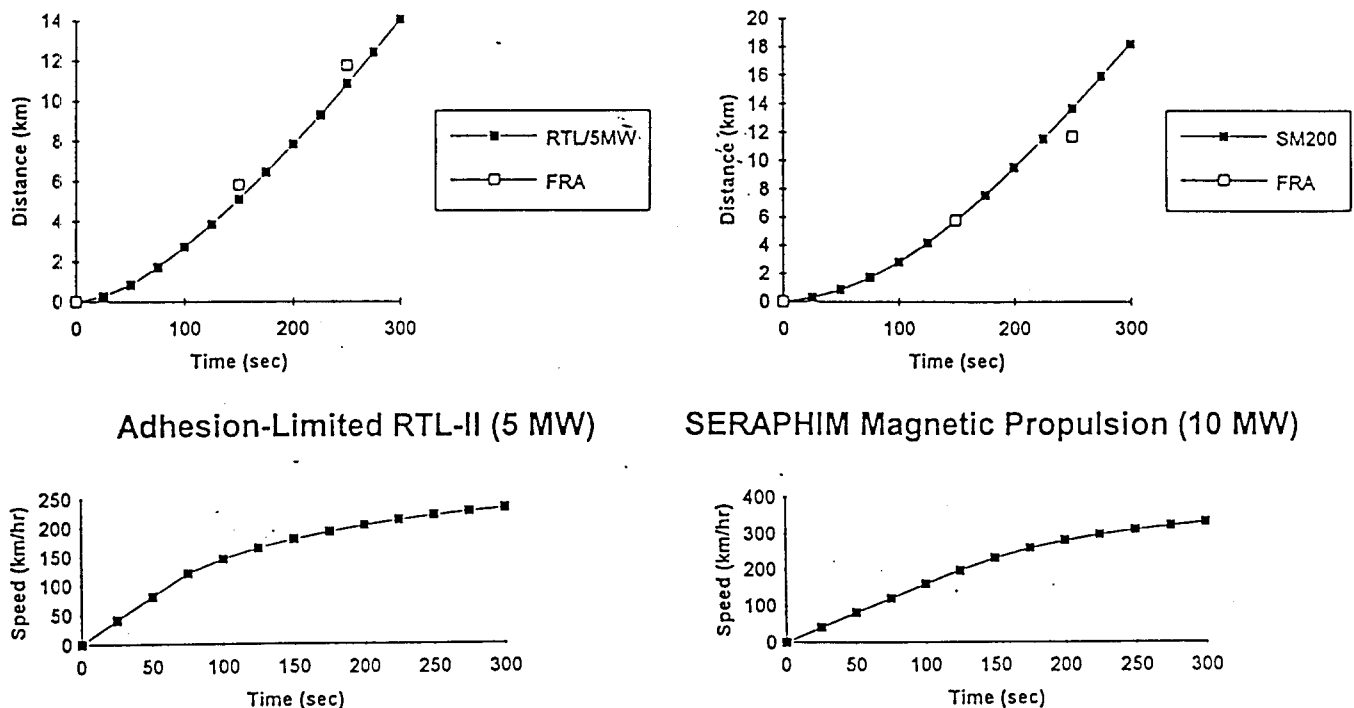
Figure 14. Distance and speed vs. time for SERAPHIM and steel wheel and rail propulsion.

For our concept study, we consider on-board power, so that the train can operate on non-electrified rail lines. The locomotive power is based on a gas-turbine power plant, generator and power conversion for 4 kV dc power. Gas-turbine information was supplied by Turbomeca Corporation. This company sells gas turbines for transportation applications, and is now testing a retro-fit of an Amtrak Turboliner locomotive with their Makila TI 1.2 MW gas turbine for Amtrak operation on the North-East Corridor. This power car weighs about 95 tons, or 86,000 kg. A larger gas turbine has been developed by Turbomeca for transportation applications such as trains and ships. The Eurodyn delivers 2.2 - 2.9 MW (2900 - 3900 hp) at a fuel consumption rate of 150 - 200 gallons per hour. Two of these engines would provide the power needed for each SERAPHIM power car. Textron-Lycoming also manufactures gas turbines for transportation applications. The TF40 engine delivers 5.3 MW (4,000 hp) continuous, 6.2 MW boost power. It weighs only 1325 pounds, is 4.3 feet long, and has a volume of 46 cubic feet. Fuel consumption for the TF40 gas turbine is 280 gallons per hour, using kerosene, diesel, or jet fuel.

Passenger-car parameters were taken from the present Amtrak fleet, the Grumman Maglev vehicle and the German Transrapid TR07 designs. The Amtrak heritage coach cars have 72 passenger seats, and weigh about 66,000 kg. The frontal cross-section is 10 m^2. The passenger cars may be lightened if new materials and fabrication approaches are taken, as with the German Intercity Express (ICE) train. To estimate the minimum weight that might

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be achieved, the light-weight vehicle designs from the Maglev study were used. Maglev vehicle mass for the Bechtel, Foster-Miller, Grumman, and TR07 maglev vehicles are all around 600 kg/seat. Such a SERAPHIM passenger vehicle thus would weigh about 45,000 kg, or 99,000 pounds. In this case, the maximum power requirement is reduced to 10 MW.

SERAPHIM PERFORMANCE, COST, AND MARKET ANALYSIS

The purpose of this section is to develop a preliminary analysis of the market potential of the pulsed linear induction motor for high speed rail travel. There are a number of uncertainties in such a study, but this analysis should be useful in guiding further development of the technology. The approach taken in this study is to define a conceptual train around the SERAPHIM technology, so that we can make estimates of the vehicle requirements, such as power, weight, cost, development needs, etc. From this conceptual vehicle design, we estimate the system-level requirements, using current industry standards and systems studies such as the National Maglev Initiative (NMI). Finally, the market potential is obtained from corridor studies from the NMI program and other published literature. From these data, we attempt to project the cost of a ticket for several corridors, based on the costs and expected ridership. The final estimates of cost are of course not well defined at this time, but are useful in differential comparison to other high speed rail and Maglev technologies.

We believe at this time that the technology development costs of the SERAPHIM concept are minimal, since the technology for power, propulsion coils, and railways are all well in hand. Additional development for the technology involves engineering demonstrations. The larger uncertainty is the market potential, the route planning, the sharing of right-of-way with other rail or highway systems, and the phased implementation of such a high speed rail network. These issues will be important to the next phase of implementation.

Transportation System Cost Estimates

Table 3 gives the cost estimates for the major components of a SERAPHIM-based transportation system. Engineering estimates for the SERAPHIM motor were developed from our experience with the SERAPHIM feasibility demonstrations and experience with power conditioning and switching. The engineering cost estimates from present high-speed rail service and the National Maglev Initiative program were used as a basis for many of these estimates. Where possible, we have made direct comparisons with high-speed rail or NMI component costs. When the requirements were different but scaleable, we scaled those costs to the SERAPHIM requirements. New cost estimates were made as necessary by engineering staff at Sandia. The comment line on the Table gives the basis for the estimates.

		Table 3		
		Cost Estimate for SERAPHIM Technology		
Component	Cost	Basis for estimate (Ref.)		Maglev Comparison (8)
Reaction Rail	$0.3 M/mile	Material, Fabrication, & Installation		
Improvements to existing rail	$0.4 M/mile	Various industry analyses		
Elevated Railway	$9 M/mile	Bechtel; Parsons, Brinkerhoff (10,11)		$ 9 M/mile
		Dual railway, 5 m elevated, 15 degree tilt		
Grade-Level railway	$ 3 M/mile	TGV Estimate (8)		$ 4 M/mile
Grade-Safety Enhancements	$ 0.5M/mile	$ 1M/crossing, 1 crossing every 2 miles (14)		$ 1 M/mile
Electrification	$ 1 M/mile	Grumman (12)		$ 6 M/mile
		Sub-stations, feeder and transmission lines		
Communication and Control	$ 0.5 M/mile	Bechtel (10)		$ 0.5 M/mile
Stations	$2M each	Renovation costs		$ 1 M/mile
Maint Facilities	NA	Bechtel (10)		$ 0.5 M/mile
Vehicles				
Passenger Car	$ 2.0 M	TGV (13)		$2.0 M
Power Car (6 MW)	$ 3.0 M	GM Genesis Locomotive x 1.5		NA
Elecrified line power car	$2.0 M	TGV (13)		
Indirects @ 50%	Sub-total*0.5	Bechtel (10)		
- Taxes, Overhead, Fees, etc				
Total: New Elevated Railway	$14 M/mile	Elevated railway		$ 25 M/mile
Total: New Grade-level railway	$ 6 M/mile	Grade-level Railway		$20 M/mile
Total: Upgrade to Existing rail	$ 2 M/mile	Track upgrade, reaction rail, limited facilities		NA
Increment for Electrification	$ 1 M/mile			
Train set (5 vehicles)	$ 10 M	Electrified line (220 passengers)		$10M
	$ 12 M	Self-powered (220 passengers)		

Market Analysis and Fare Basis

Tables 4 and 5 present calculations of costs and revenues from several case studies. The market studies conducted for the NMI program were used to estimate the degree of ridership and traffic loading that could be expected for several high-density routes. The NMI Final Report (Ref. 8) evaluated 16 possible high speed corridors, estimating the cost, revenue, and ridership for each. A similar study was conducted for a number of additional corridors. (Ref. 9) Results from some of these corridors are tabulated in Table 4. Right-of-way costs are not included here, with the assumption that right-of-way is shared largely with existing rail or highway systems. The cost/revenue factor is the ratio of total system capital and operating costs to the expected revenue potential for the corridor. A number lower than 1 indicates that the corridor has the potential to cover the full costs. Generally, transportation costs are partially supported by government funding, either directly or indirectly. For instance, airport construction and maintenance, air traffic control, highway construction, maintenance, and safety controls are direct public supports for air and automobile transportation. Likewise, federal and state governments provide about 20% of Amtrak operating costs. Following this practice, then, a route that has a cost/revenue ratio as high as 1.2 could be considered appropriate for consideration.

Case #	1	2	3	4	5
		Table 4			
	SERAPHIM High Speed Train				
	Cost and Revenue Case Studies				
Route Data	NE Corridor	NE Corridor	SF-SD	LA-SF	LA-LV
Travel Distance (miles)	467	300	540	395	285
Fraction Elevated railway	0.1	0.1	0.1	0.1	0.1
Fraction existing railway	0.9	0.9	0.5	0.5	0.9
Average Speed (mph)	150	100	120	120	150
Travel Time (hours)	3.1	5	4.5	3.3	1.9
Peak Speed (mph)	200	200	200	200	200
Estimated Market:					
Market information Ref.	Ref. 8	15% of market	Ref. 8	Ref. 9	Ref. 8
Total Trips per Year (million)	23.5	3.5	17	10.6	6.8
Total trips per day	64300	9600	46600	29000	18600
Trip Time (hours)	4	6	5	5	3
Peak/Average Loading	1.2	1.2	1.2	1.1	1.3
Passenger capacity per train	220	220	220	220	220
Fraction capacity	0.8	0.8	0.8	0.8	0.6
Fraction Maintenence Time	0.1	0.1	0.1	0.1	0.1
No. Train sets	80	18	88	45	20
Cost per Train set ($M)	10	10	12	12	12
System Costs					
Elevated Rail Cost ($M/mile)	14	14	14	14	14
At-grade rail cost ($M/mile)	2	2	6	2	2
Miles elevated	50	50	54	40	30
Miles at Grade	417	250	486	355	255
Railway Cost ($M)	1534	500	2600	1900	930
Station Cost ($M)	50	20	40	20	20
Total cost for Train sets	800	180	1060	540	240
Capital Cost ($M)	2384	700	3700	2460	1190
Debt Servicing (5%/yr)	72	21	110	74	36
O&M Cost ($M/yr)	900	130	730	340	160
$0.08/passenger-mile					
Total 10 year cost ($M)	12100	2210	12100	6600	3150
Required ticket cost/mile	$0.11/mile	$0.14/mile	$0.13/mile	$0.16/mile	$0.16/mile
for break-even					
Break-even ticket price	$51	$63	$70	$62.00	$50
Annual Revenue Capacity	$2290M	$344M	$1330M	$1000M	$450M
Cost/Revenue Capacity	0.53	0.64	0.93	0.7	0.7

	Table 5				
	SERAPHIM High Speed Train				
	Cost and Revenue Case Studies				
Case #	6	7	8	9	
Route Data	ElPaso-Den.	ElPaso-Den.	El Paso-Alb.	El Paso-Alb.	
Travel Distance (miles)	733	733	254	254	
Fraction Elevated railway					
Fraction existing railway	1	1	1	1	
Average Speed (mph)	40	80	80	80	
Travel Time (hours)	18	9.2	3.2	3.2	
Peak Speed (mph)	79	100	100	100	
Estimated Market:					
Market information Ref.	Ref. 15	Ref. 15	Ref. 15	Ref. 15	
Total Trips per Year (million)	0.11	0.11	0.06	0.22	
Total trips per day	2	4	4	6	
Trip Time (hours)	18	10	4	4	
Peak/Average Loading	1	1	1	1	
Passenger capacity per train	250	150	100	100	
Fraction capacity	0.6	0.5	0.41	0.7	
Fraction Maintenence Time	0.2	0.2	0.2	0.2	
No. Train sets	2	2	2	2	
Cost per Train set ($M)	0	7	4	4	
System Costs					
Elevated Rail Cost ($M/mile)					
At-grade rail cost ($M/mile)		0.3	0.3	0.3	
Miles elevated					
Miles at Grade	733	733	254	254	
Total Railway Cost ($M)	75	220	76	76	
Stations ($M)	4.3	4.3	1.5	1.5	
Trainset Costs ($M)	0	14	8	8	
Total Capital Costs	79.3	241	85	85	
Debt Servicing (6%)	2.4	15	2.6	2.6	
Total O&M cost per year	11.1	11.1	2.1	2.1	
Total 10 year costs	214	502	132	132	
Required ticket cost/mile for break-even	$0.26/mile	$0.68/mile	$0.87/mile		
Break-even Ticket Cost	194	468	220	60	
Annual Revenue Capacity	7.8	7.8	4	12	
Cost/Revenue Capacity at Full cost recovery	2.74	6.4	3.3	1	
Operating Cost/Revenue	1.4	1.4	0.5	0.2	

The North East Corridor Case #1 costing assumes that the entire line from Boston to Washington is upgraded with reaction rail plates and other infrastructure to accommodate high-speed travel. Most of this line is electrified presently, and will be completely electrified within 5 years. Therefore, we assume that the power car will not require an on-board power source. The track upgrade is assumed to cost $2M per mile for 90% of the line, to cover the costs of rail improvements, reaction rail, and safety enhancements at all crossings. It is further assumed that 10% of the track should be elevated, particularly within cities. The revenue projection is from Reference 8. The calculated cost/revenue ratio is 0.53, indicating the potential for full cost recovery and profit. The second case in Table 4 assumes that only 300 miles of the NE Corridor is retrofitted for the SERAPHIM train, with the remainder being conventional propulsion at lower speed. In this case, the initial capital investment is substantially reduced. The ridership potential is assumed to be 15% of that from Reference 8. The cost/revenue ratio is again lower than 1.

Similar analyses are shown in Table 4 for California and Nevada routes. These routes (San Francisco to San Diego, Los Angeles to San Francisco, and Los Angeles to Las Vegas) have been proposed for both Maglev and High Speed Rail systems. Initial capital investments are on the order of $6M per mile. The results show the potential for full cost recovery for SERAPHIM for these lines, at ticket prices around $0.15/mile, which is competitive with current airline and Amtrak pricing.

A study commissioned by the New Mexico Highway and Transportation Department, as part of the Intermodal Surface Transportation Act (Ref. 15) provides information on a north-south route from El Paso, Texas, to Denver, Colorado. This study is summarized in Table 5, Case #6. Existing rail lines were to be upgraded at a cost of $79M, principally for track and signaling improvements. The cost of these improvements was to be funded directly by the states. The ratio of Cost/Revenue is 2.7, indicating that substantial funding support for the line would be required from local, state or federal governments. The break-even ridership projection was 175,000 passengers per year. Increasing the maximum speed on this track, through improvements in propulsion technology and signaling controls, could attract additional riders to the train, principally from airlines or private autos. To attract ridership to 175,000 per year, the train would require almost 50% of the present airline traffic.

Case #7 in Table 5 uses the El Paso-Denver route projections from Reference 15, with the addition of the costs incurred for the SERAPHIM system. The principal added cost is the reaction rail, which is about $300,000 per mile. This is a substantial increased cost, and makes the El Paso-Denver line too expensive for the projected revenue basis. The El Paso-Albuquerque line is shorter and much less expensive, as shown in Case #8, but still is too expensive for the revenue and ridership projections of the near future. Case #9 takes the El Paso-Albuquerque cost estimates and calculates the required ridership for break-even. In this case, the line would cover the complete cost of operations and infrastructure with 200,000 riders per year, at a competitive ticket price of $60. The present market is only about 60,000 riders per year, so substantial population and tourism growth is needed to fully recover costs.

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From these brief calculations, general trends emerge. The SERAPHIM system costs are roughly 25% of the projected costs for a comparable Maglev system when elevated lines are compared, but SERAPHIM can be as low as 12% of the Maglev cost when existing railway can be used. The added costs of Maglev come from the powered roadway and the increased costs for electrification of the line. The SERAPHIM cost is comparable to that for steel-wheel high-speed rail. To fully recover costs, a potential route must have sufficient ridership to amortize the infrastructure and operating costs at a competitive ticket cost. The definition of competitive ticket cost involves cost compared to airline prices, as well as qualitative advantages of travel time and convenience. Airline ticket prices usually range around $0.15-$0.20 per mile. The routes shown in Table 4 all meet this requirement, and have a cost/revenue ratio less than one. These routes have a rider potential of the order of 20,000 riders per year per mile. This figure appears to be a good rule-of-thumb for estimating route potential for intercity routes of the order of 200 - 500 miles.

OUTLINE FOR FUTURE DEVELOPMENT PROGRAM

The following tasks are needed to take the SERAPHIM concept from its present stage of research to a demonstrated technology for the high-speed rail environment. The following tasks are needed to demonstrate the engineering aspects of the motor operation, first in a single-module power demonstration, then a multiple-module vehicle demonstration, then a train set demonstration. The early tests are designed to reduce the cost and technical risk by utilizing a limited length of railway and a vehicle of opportunity, which could be a retired passenger locomotive, rail car, or specially-constructed test car. Successful completion of each task is the milestone for continuation to the next task.

TASK 1. Motor Prototype Design and Test

Objective: Design and test a prototype motor, including coil set, power switching, and control unit for demonstration at full power. The coil set will be operated at 100 kW continuous operation for extended periods of time to evaluate efficiency, thrust, braking, control, and cooling. Power controls and switching will utilize commercial solid-state switch components and off-the-shelf hardware.

Description: A prototype pulsed induction motor will include a 4 kV power supply, two to four parallel modulators, load coils and a linear or rotary reaction "rail." Initial tests may be conducted on the existing or modified linear rack to demonstrate impulse coupling, efficiency and basic control features. A "rotary rail" dynamometer will be required for startup, acceleration, and high speed tests. The "rotary rail" should have controlled loading with a dynamometer to simulate different operating conditions and provide a test bed for endurance testing of the high power electronic circuits. It will be the goal of this phase to demonstrate a reliable working prototype pulsed induction motor ready for adapting to a rail car experiment.

TASK 2. Vehicle Demonstration Design and Test

Objective: Operate a rail test vehicle with a pulsed LIM to demonstrate performance in an actual rail operation environment. Demonstrator will be powered by an on-board power plant. Vehicle will be operated to extended speeds on an appropriate test track, such as the facility at the Transportation Test Center in Pueblo, CO. Multiple units of the Prototype Motor design from Task 1 will be used. Figure 15 is an illustration of the basic layout for the test vehicle, in this case a simple vehicle based on a rail flat car.

Description: The desired vehicle would be a retired locomotive or transit car, flat car, box car, or caboose. If test car has no on-board power, diesel-electric or other power generating equipment will be installed. If power from overhead catenary is available, power collection and conditioning equipment will be installed. Six coil sets at minimum will be installed, with 600 kW power, for demonstrating acceleration, high speed capability, control, and braking. Remote control telemetry and data link enables unmanned operation of the test vehicle for safety reasons. Reaction rail will be installed at test track for up to 1 mile in length. At low speed, evaluate operation and demonstrate acceleration from dead stop, control, and braking. Progressively work to higher speeds, characterizing vibration, handling characteristics, maximum thrust.

TASK 3. Follow-on Demonstration of Prototype Locomotive/Train set

Objective: Modify a locomotive and train set for SERAPHIM power. Use the existing locomotive power for low speed and station entrance-exit. Use the SERAPHIM propulsion for high speed corridor. Approximately 20 miles of high speed track would be converted for initial testing.
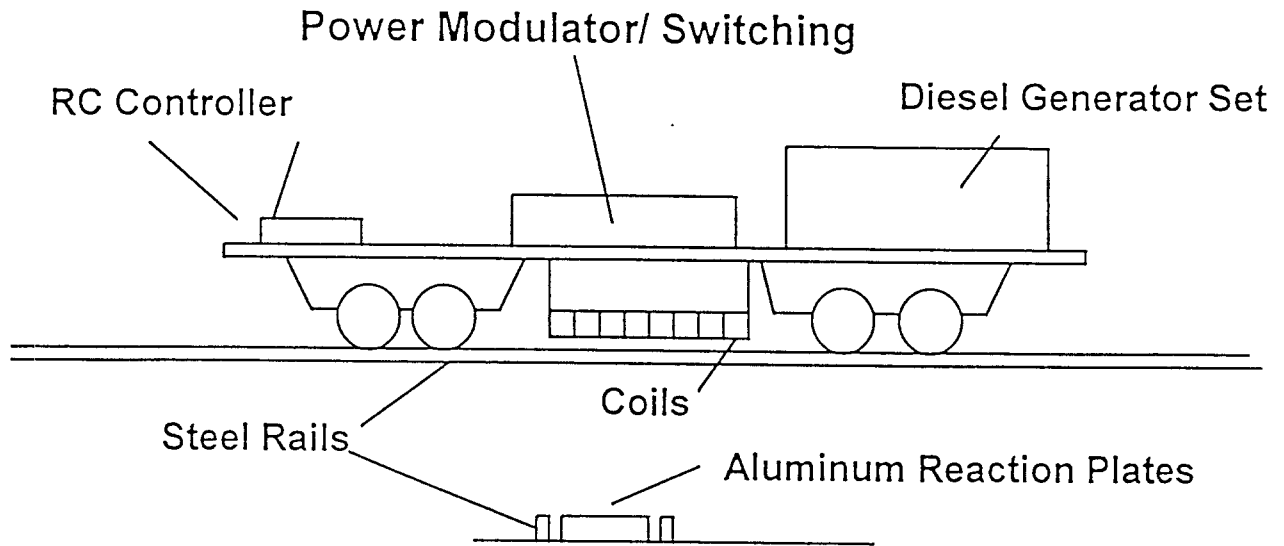
Figure 15. SERAPHIM-powered car demonstration.

SUMMARY

Linear induction motor technology is mature, and has been demonstrated already on a limited basis in high speed rail applications. The performance improvements that can be achieved with pulsed magnets allow the pulsed linear induction motor to be made more compact and lighter weight. Introduction of magnetic propulsion technology for high speed rail offers the potential for improving propulsion for high speeds without creating additional rail damage. The pulsed linear induction motor technology has been evaluated in this study. The conceptual design for a SERAPHIM trainset for 200 mph passenger service appears to be feasible. The development costs of the SERAPHIM technology are minimal, since the technology for power, propulsion coils, and railways are all well in hand. Additional development for the technology involves engineering demonstrations for the high-speed rail environment. The following tasks are required to demonstrate sequentially the engineering aspects of the motor operation: (1) a single-module power demonstration, (2) a multiple-module vehicle demonstration, (3) a train set demonstration. The early tests are designed to reduce the cost and technical risk by utilizing a limited length of railway and a vehicle of opportunity, which could be a retired passenger locomotive, rail car, or specially-constructed test car.

The larger uncertainty at this time is the market potential, the route planning, the sharing of right-of-way with other rail or highway systems, and the phased implementation of such a high speed rail network. Preliminary route analysis suggests that larger population density centers in the country, such as the NE Corridor and the California routes, have sufficient

ridership potential to recover operating and capital costs. The necessary ridership potential is of the order of 20,000 passengers per mile per year. The political and economic issues of route selections and investment are beyond the scope of the present technology study, but will be important issues to be resolved in further phases of implementation.

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